Quantifying sublimation of buried glacier ice in Beacon Valley

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Summary A remnant of Taylor Glacier ice rests beneath a 40-to-80-cm-thick layer of sublimation till in central Beacon Valley, Antarctica. Our 1-D vapor diffusion model, with input from micrometeorological data collected during the 2004 austral summer, shows that vapor flows into and out of sublimation till at rates dependent on the non-linear variation of vapor concentration with depth. Although measured meteorological conditions during the study interval favored a net loss of buried glacier ice (~0.017 mm over 42 days), an average rate of ice sublimation that is consistent with a loss of 400 m of ice over 8.1 Ma (an amount suggested by Potter et al., 2003) is permissible if local temperatures decrease by ~3ºC; relative humidity increases by 15%; or snowmelt infiltration equals ~0.001 mm/day. Our model results are consistent with the potential for long-term survival of buried glacier ice in the hyper-arid upland zone of the Dry Valleys.

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Introduction

Interest in buried glacial ice has gained considerable attention in recent years due to its potential as an archive for long-term climate change. Geochemical analyses of ice stored in stagnant debris-covered glaciers in the western Dry Valleys region of Antarctica may ultimately extend records back into the Miocene, well beyond that now possible from analyses of ice at Vostok and Dome C (e.g., Petit et al., 1999, EPICA, 2004). At issue, however, is whether these stagnant debris-covered glaciers can maintain a core of glacier ice for millions of years, or whether ice sublimation would remove all traces of original glacier ice over these time scales (e.g., Sugden et al., 1995, Hindmarsh et al., 1998, Schaefer et al., 2000, Ng et al., 2005).

In order to assess the potential for multi-million year-old buried glacier ice in the Dry Valleys, we modeled summertime vapor flow through an ancient sublimation till that caps buried glacier ice in central Beacon Valley. The age of this ice, sourced from Taylor Glacier, is debated (van der Wateren & Hindmarsh, 1995), with published ages ranging from ~300 ka (Ng et al., 2005), to >2.3 Ma (Schaefer et al., 2000, Marchant et al., 2002), to >8.1 Ma (Sugden et al., 1995). In this paper we outline the range of climate conditions necessary to preserve the buried ice for millions of years. Our approach is to first calculate rates of summertime sublimation and vapor flow under existing climate conditions (atmospheric temperature and relative humidity, solar radiance, soil temperature and moisture) and then calculate sublimation rates for a range of plausible climate scenarios that may have occurred in this sector of Antarctica over the last several million years.

Geologic Setting

The buried ice in central Beacon Valley is stagnant (zero horizontal motion, Rignot et al., 2002) and contains 3 wt% debris; it rests beneath a thin sublimation till that is on average 50 cm thick (Fig. 1). Debris within the ice is commonly concentrated in bands up to 10 cm-thick and includes clay-to-cobble-sized grains, clasts of Ferrar Dolerite, Beacon Heights Orthoquartzite, and granite erratics foreign to Beacon Valley (Marchant et al., 2002). Sublimation of the ice has thus far produced the protective sublimation till that mantles the ice. Schaefer et al. (2000) showed that the rate of ice sublimation decreases with increasing till thickness and Marchant et al. (2002) found that the development of high-centered polygons at the till surface also exerts a strong control on ice sublimation. Initially rates of sublimation are highest at immature polygon troughs, but as troughs deepen via sublimation, they become preferred sites for wind-blown snow; this snow cover reduces underlying ice sublimation and in many cases leads to the formation of secondary ice. To a first order, then, ice sublimation is controlled by the rate of ice loss at polygon centers.

Existing environmental conditions in central Beacon Valley

We deployed a series of HOBO Micro Station data loggers and "Smart Sensors" (manufactured by Onset Computer Corporation) along a vertical profile at the center of a well-formed polygon in central Beacon Valley. The diameter of the polygon is ~17 m and the nearest trough from the profile is about ~6 m distant. Data for solar radiance, relative humidity, atmospheric and soil temperature, and soil moisture were collected at 15-minute increments.

Solar Radiance

Incoming solar radiance during the study period ranged from 14.4 W/m^2 to 903.1 W/m^2. Cloudless days show smooth sinuous radiation curves with the amplitude of the curve being a function of solar aspect.

Relative Humidity (RH)

RH at 2 cm above the till surface ranged from 6.75% to 90.75% with an average of 36.0%. Although fog and snowfall occurred for a minimum of 10 days within the study period, *RH* sensors recorded a maximum of 90.75%, and not 100% as expected. The explanation is that at very low atmospheric temperatures (<0°C), the HOBO sensors underestimate *RH* values (Onset Computer Corporation, 2002).

Temperature

Atmospheric temperatures at 2 cm rarely rose above 0ºC, varying from a high of 3.3ºC to a low of -16.0ºC during the austral summer. Due to the high solar radiance and relatively low albedo of the till surface (albedo of dolerite rocks is ~0.07; Campbell et al., 1997), the ground-surface temperatures often exceeded atmospheric temperatures (as measured at 2 cm above the ground surface) by 5 to 10ºC. Daily variations in atmospheric temperature were propagated through the sublimation till, but were attenuated abruptly at depth (Fig. 2); temperature inversions (warmer temperatures at depth) were common down to 30 cm. The maximum penetration of the 0ºC isotherm in the sublimation till reached 14.6 cm (35.4 cm above the buried ice surface).

Soil Moisture

Sensors at 2-cm depth recorded elevated soil moisture on six occasions; field observations indicate that this meltwater was derived from the melting of recent snowfall.

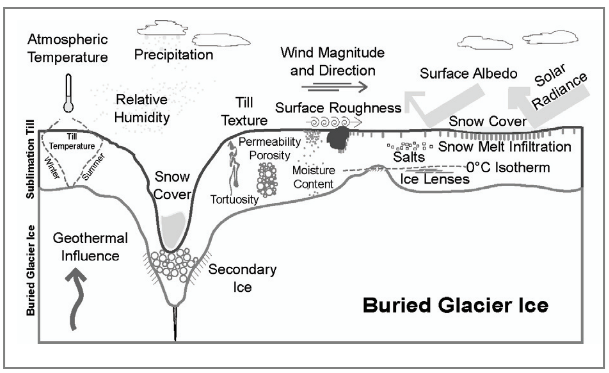

Figure 1. Factors that influence the stability of buried glacier ice. Meteorological factors include wind speed and direction, solar radiance, precipitation, atmospheric temperature, and atmospheric relative humidity. Geological factors include till texture, till thickness, surface albedo, the formation of ice lenses and secondary salts, the development of thermal contraction cracks, and geothermal heat.

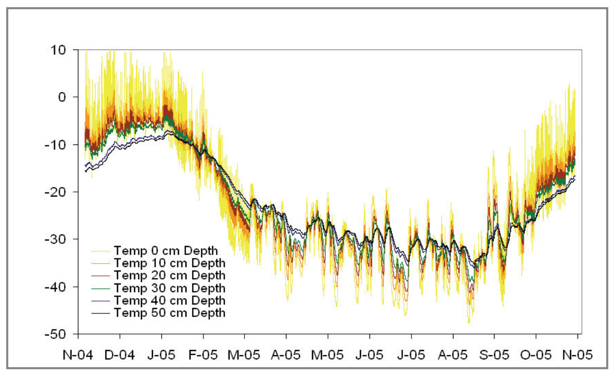

Figure 2. Measured soil temperatures at 0, 10, 20, 30, 40, and 50-cm depth in central Beacon Valley. Oscillations dampen rapidly with depth. Daily temperature inversions (i.e., regions where soils at depth are warmer than near the surface) are restricted to the upper 40 cm of the till. Graph represents one full year of climate data in Beacon Valley although initial studies concentrated solely on summertime sublimation rates.

Calculated vapor flux through sublimation till

The vapor flux within a porous medium is governed primarily by three mechanisms: molecular diffusion of water vapor in the pore space, advection of air through the till, and molecular diffusion from temperature gradients. Studies by Hudson et al. (in review) and Schorghofer & Aharonson (2005) suggest Fickian diffusion is the dominant transport of water vapor in cold arid environments. Our model stresses Fickian diffusion and ignores the very minor effects of Knudsen diffusion. Given the above, the molecular diffusion of water vapor through pores in sublimation till can in a general fashion be expressed using Fick's First Law. In a porous medium we add a porosity and tortuosity term (ϕ and b respectively), and thus, a model for vapor diffusion is

$$\frac{\partial \rho}{\partial t} = -\frac{\phi D}{b}\left(\frac{\partial^2 \rho}{\partial z^2}\right) \tag{1}$$

where ρ is the water vapor density, t is time, D represents the diffusion coefficient, and z is depth. Our parameters for porosity, tortuosity, and the diffusion coefficient are 0.41, 2, and ~0.16 $cm^2\ s^{-1}$ respectively, and are all within published values for Dry Valley soils (Hindmarsh et al., 1998, McKay et al., 1998, Pringle et al., 2003).

Model results show that vapor flux is both outward to the atmosphere and inward toward the buried-ice surface (Fig. 3). This complex vapor-flow pattern differs from that discussed in Hindmarsh et al. (1998), whose model evaluated unidirectional vapor flow from the buried-ice surface to the atmosphere. It is one explanation for our relatively low rates of net sublimation of the buried glacier ice as compared to those derived by Hindmarsh et al. (1998).

The maximum outward flux rate at the buried ice surface is 5.9×10^{-7} kg/m^2 min; the maximum inward flux rate at this same depth is -1.3×10^{-7} kg/m^2 min (the negative value designates downward vapor flux). Because the rates for inward and outward fluxes are of the same order of magnitude, this finding highlights the importance of subtle changes in temperature and *RH* on buried-ice stability.

We calculate an average daily (summertime) sublimation rate of 3.9×10^{-4} mm/day. Vapor flux moved downward into the till during ~10% of the study interval; this vapor reached the surface of the buried glacier ice during about 1% of the study interval. The implication is that the preservation of the buried ice represents a balance between outward ice loss via vapor diffusion to the atmosphere and inward vapor flux from the atmosphere to the buried-ice surface. During the study period, environmental conditions favored sublimation (over ice accretion at depth) and a net ice loss of buried glacier ice of 0.017 mm.

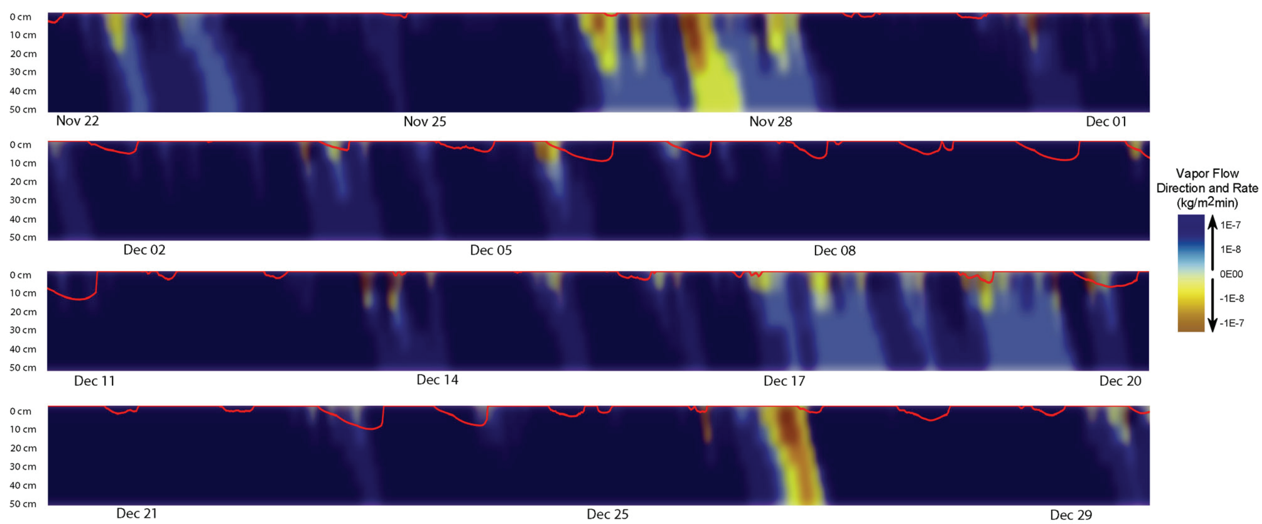

Figure 3. Calculated model results for vapor flux in the sublimation till for the austral summer, 2004. Results are plotted as colored contours (see scale bar for details). Blues indicate outward flux to the atmosphere; browns and yellows, inward flux to the ice surface. The red line represents the depth of the zero degree isotherm.

Implications for long-term survival of buried glacier ice

Assuming our modeled summertime sublimation rate can be extrapolated over an entire year (a scenario which likely overestimates annual ice loss), then our calculated annual ice loss is ~1.4×10^{-4} m a^{-1} (over 8.1 Ma, this results in a vertical ice loss of ~1150 m). This rate is an order of magnitude less than that calculated by Hindmarsh et al. (1998). However, given that summertime sublimation exceeds wintertime sublimation (Hindmarsh et al., 1998), a more realistic assessment for annual ice loss might be 1.05×10^{-4} m a^{-1} (calculated using a reduced wintertime sublimation rate equal to 50% of the summertime sublimation rate). Applying this lower rate over 8.1 Ma yields a total vertical ice loss of ~850 m.

Potter et al., (2003) showed that the level of remnant Taylor Glacier ice in central Beacon Valley has lowered by ~400 m. Their estimate is based on the elevation difference between the mapped upper limit of sublimation till in central Beacon Valley (Granite drift) and the current elevation of remnant ice. Using our model for vapor diffusion, an appropriate sublimation rate accounting for 400 m of ice loss (over 8.1 Ma) could be achieved given any one of the following changes in average climate conditions: a decrease in atmospheric temperature of ~3°C; an increase in *RH* of ~15%; or snowmelt infiltration equal to ~0.001 mm/day (Fig. 4). To help assess whether such conditions are feasible, we examined past climate records derived from ice cores in central Antarctica and from nearby Taylor Dome, the latter being only 30-km west of Beacon Valley. The magnitude of temperature variation at both sites is similar. The record at Vostok shows that during the last five glacial-interglacial cycles, near-surface atmospheric temperatures varied by 12ºC (Petit et al., 1999, Indermühle et al., 2000) and the average surface temperature was ~3°C below today's value (Petit et al., 1999). Although the ice core records do not allow for speculation of Pliocene and late Miocene climate in the Dry Valleys, they do suggest that today's climate is on average warmer than the last ~500 ka.

Conclusions

Our results suggest that buried ice in central Beacon Valley is extremely sensitive to small changes in climate and that buried ice could survive for millions of years given very minor changes in local climate conditions.

Assuming that there is no significant departure in seasonality and that rates for summertime sublimation can be applied year-round (an overestimate for annual ice sublimation), a 400 m ice loss over the past 8.1 Ma (e.g. Potter et al., 2003) could be achieved with any one of the following changes: atmospheric temperature drops ~3ºC; *RH* rises 15%; snowmelt equals ~0.001 mm/day (Fig. 4). Such changes are reasonable, given that Antarctic ice-core records show that air temperatures over the last 5 glacial-interglacial cycles were on average ~3°C colder than today (Petit et al., 1999). An increase in cloud cover alone might yield the requisite conditions for long-term ice preservation; this would likely lead to an overall decrease in air temperature, an increase in *RH*, and if accompanied by precipitation as would be expected, a potential increase in the magnitude of snowmelt.

The results presented here are conservative in that our model does not consider the reduction in vapor flux (ice loss) that would accompany 1) the progressive increase in tortuosity that might arise from the development of salt and/or ice crystals in pore spaces (Bao et al., 2002), 2) the burial of ice and sublimation till beneath long-lived perennial snowbanks and/or ice (Marchant et al., 2002), and 3) the influence of surface rough-ness on atmos-phere-till-boundary layer conditions that could result in elevated *RH* across the till surface (e.g., Fig. 1).

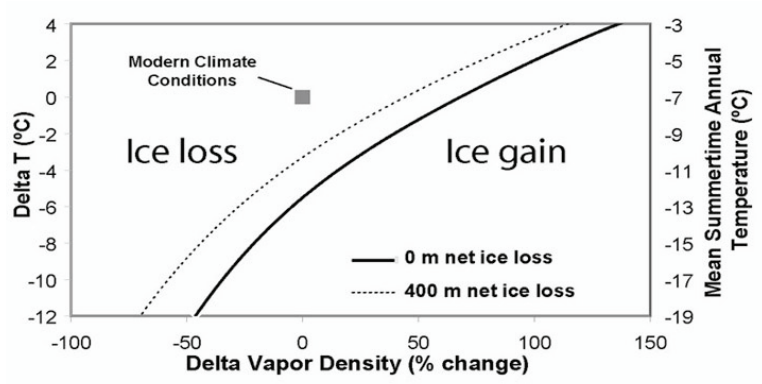

Figure 4. Stability field for buried glacier ice in central Beacon Valley relative to changes in summer atmospheric temperature and vapor density (2 cm above the ground surface). (Adapted from Kowalewski et al., 2006)

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